

# **Electrical Conduction Behaviour of The Cement Matrix Composite with Wireless Intelligent Sensor Network and Embedded Piezo Transducer in Concrete for Automatic Structural Health Monitoring in Bridge Structures**

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**ABSTRACT:** As structural materials, cement-matrix composites have received much attention in terms of their mechanical properties. The ability to provide non-structural functions allows a structural material to be multifunctional, thus saving cost and enhancing durability. The ambient vibrations created by the civil structure (bridge) are converted into electrical signal by the property of the micro planar piezo-electric sensor element. The use of the piezo- patches as transmitting and sensing element the life cycle of civil infrastructure such as bridges and buildings can be monitored. The design of the wireless sensor network and the concrete matrix is also aimed at applications of structural health monitoring. The practical applicability of the sensor network is increased through utilization of computational intelligence and support of signal generation capabilities, based on the method of modal strain energy. The automation tasks in this paper include automation of the modal identification through ambient vibrations, classification of the acquired mode shapes, and automatic evaluation of the structural health and embedded ultrasonic transducers for concrete property diagnosis. This review is thus based on using the energy efficiently by conserving the electricity and increasing the life cycle of the civil structures by the proper proportion of the composites and monitoring it.

**KEYWORDS:** Cement-composite-concrete-electromagnetic-thermoelectric-Piezoresistive-resistive-wireless-sensor networks-structural health monitoring-ambient vibrations-autonomous systems- modal Strain energy- Piezo-transducer.

## **I. INTRODUCTION**

Life cycle monitoring of civil infrastructure such as bridges and buildings is critical to the long-term operational cost and safety of aging structures. Knowledge of the structure's health, load bearing capacity, and remaining life is the primary goal of any strategy of Structural Health Monitoring (SHM). Maintaining and improving the condition of bridges is critical to the structural integrity and cost effectiveness of the transportation system. Bridges constitute the most vulnerable element of the transportation infrastructure. An out-of-service bridge creates economic losses both for the bridge users (in terms of traffic delays and detours) and for the bridge and road operators. The majority of the bridges in India are small and medium span structures, located on local (secondary) or rural roads. The two main reasons for deterioration of the transportation infrastructure: rapid aging of the bridges and significant increase in traffic levels, placing the wear and tear on many bridges beyond the levels those they were designed to handle. The increased traffic levels have put a research on its vibration. This stress produced can be thus used by the Piezo electric transducers for producing equivalent amount of voltage. This paper is mainly concentrated on using the transducer in the metropolitan and other busy bridges.

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## II. LITERATURE SURVEY

Habitat monitoring is the leading application of the wireless intelligent sensors. Structural Health Monitoring is closely related to the dynamics of the structures, and the basic principle is during time to identify changes in the dynamic response which may be related to a structural damage. Sensor technology and sampling and filtering of data are other key areas enabling a structural identification. Most of the thesis relates to the work of structural health monitoring with all the above mentioned apparatus. To add a fuel to it and to increase the efficiency of the structural health monitoring, a sensor is placed in the bridge structure to generate power. The generated power can be used for various applications.

## III. STRUCTURAL VIBRATION

Vibration is a mechanical property. The various types of vibration that is produced in the deck are grid vibration, drag-through vibration and conventional vibration. *Grid vibration* refers to the process of vertical insertion of several vibrators in a matrix pattern. *Drag-through vibration* refers to a process by which vibrators attached to the finishing carriage were dragged transversely through the deck concrete just above the top reinforcement layer. *Conventional vibration* refers to the standard practice of consolidating bridge deck concrete. The vibrations produced act as a strain for the Piezo electric transducer. Since the strain produced in these concrete structures are at the level of microstrain to nanostrain level. To detect the strain microelectromechanical(MEMS) system technique is used for manufacturing the Piezo electric transducer.

## IV. CONDUCTION BEHAVIOUR OF CEMENT MATRIX COMPOSITES

### *Effect of strain on Resistive Behaviour*

Piezoresistivity is a phenomenon in which the electrical resistivity of a material changes with strain, which relates to stress. This phenomenon allows a material to serve as a strain/stress sensor. Applications of the stress/strain sensors include pressure sensors for aircraft and automobile components, vibration sensors for civil structures such as bridges, and weighing-in-motion sensors for highways (weighing of vehicles).

## V. SENSING THE VIBRATION

A common method for strain sensing involves the use of piezoresistive materials, of which the strain change is proportional to the resistance change. Piezoresistive strain gauges are usually applied to structures for static to low frequency strain detection. From a strain sensing perspective, it is desirable to make sensors much smaller than the host structure. A smaller sensor reduces the burden of the added sensors on the structure, preserving structural dynamics. Smaller sensors can also be used to explore local strain on structures without averaging the strain determines the kind of vibration information being retrieved. Similar to the node concept on structures, in that nodes show no displacement at a certain resonance frequency, there are also locations on structures that show no strain at certain resonance frequency while exhibiting large strain at other frequencies. The sensor location, if properly chosen, can serve as a weighting function for the sensing signal in frequency domain at the neighborhood. The concept of local strain is especially important in vibration detection as the sensor location.

## VI. SENSING ELEMENT

Microelectromechanical systems (MEMS) techniques have proven to be an efficient way of miniaturizing transducers by orders of magnitude. Various sensors based on strain detection such as pressure sensors accelerometers or atomic force microscopy sensors have been developed using MEMS technology. These sensors are typically fabricated on silicon or quartz substrates and installed into a housing for implementation. In addition to their compactness, another advantage of MEMS sensors over macro sensors is that they can be fabricated in batch, minimizing the manufacturing cost. Most microstrain sensors rely on piezoresistive effects to measure the corresponding strain. Others use capacitance change or frequency shift of a resonator fundamental mode to extract the strain information. Piezoelectric materials such as lead zirconate titanate (PZT), zinc oxide (ZnO), or aluminum nitride (AlN) are seldom used for standalone strain sensors in microscale, although they have been used extensively for MEMS surface acoustic wave

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(SAW) devices which are composed of both actuators and sensors. Piezoelectric sensors produce charges when subjected to external strain or stress. The signal strength is proportional to sensor thickness. Since MEMS sensors are considerably thinner than bulk devices, MEMS piezoelectric sensors lose sensitivity as a result of their size in comparison with larger devices. MEMS strain sensors are mostly made of piezoresistive materials, which are less vulnerable to size effect, in part because of this reason. However, piezoelectric sensors typically show better signal-to-noise ratio (SNR) over a large frequency range and are more suitable than piezoresistive sensors for vibration signal detection. Piezoelectric sensors are also capable of detecting strains in all directions simultaneously whereas piezoresistive strain gauges are usually used for strain sensing in single direction. The ultimate resolution of ZnO MEMS piezoelectric strain sensors for dynamic strain sensing and demonstrate the use of these strain sensors, which are fabricated on both silicon and steel substrates.

## VII. WIRELESS INTELLIGENT SENSOR NETWORK

The Wireless Intelligent Sensor and Actuator Network (WISAN, “the sensor network”) are designed with the goal of continuous structural health monitoring in mind. The intelligent capabilities of limited signal processing, compression, waveform generation and embedded computational intelligence (fuzzy logic and neural networks) make this sensor network almost universally applicable to a variety of SHM methods. The maximum total power consumption of a WISAN node with all devices fully on (75mW at 3V) is significantly lower than the power consumption of other sensor networks proposed for the task of structural health monitoring. The internal structure of a sensor node is shown in Fig. 1. Data acquisition modules are built around an ultra-lowpower microcontroller MSP430F1611 from Texas Instruments. The data acquisition modules each provide up to six 12-bit analog-to-digital channels, two 12-bit digital-to-analog channels, 16 general-purpose digital input/output channels, and up to 16Mbit of non-volatile EEPROM memory. The modular design allows a scalable design with a flexible number of input/output channels and relieves the network protocol controller from execution the signal processing tasks. The data acquisition modules connect to the network interface via an internal bus. The network interface module implements the network protocol based on IEEE 802.15.4 standard. A 2.4Ghz module CC2420 from Chipcon is used for the radio interface. Utilization of the MSP430 series of microcontrollers and CC2420 RF chips allows for an extremely low power design of the sensor nodes. A single MSP430 consumes about 0.84mW at 1Mhz or 7.5mW at 8Mhz, which is superior to most other microcontrollers. In addition, MSP430 consumes only about 5 $\mu$ W in the low-power mode, enabling many years of battery life in standby. The CC2420 is a low-power, low-cost, IEEE 802.15.4 compliant transceiver designed for RF applications in the 2.4 GHz unlicensed ISM band. The transceiver module provides 16- channel direct sequence spread spectrum modem with 2 Mchips/s and 250 kbps effective raw data rate, low power consumption (RX: 60 mW, TX: 52 mW), effective range 10 to 75 meters, programmable output power, hardware MAC encryption and authentication (AES-128), signal strength indicator and battery monitor. The maximum total power consumption of a WISAN node with all devices fully on (75mW at 3V) is significantly lower than the power consumption of other sensor networks proposed for the task of structural health monitoring.

Such low power consumption allows prolongation of the battery life and extension of the replacement cycle to several years, or better yet, utilization of the energy of ambient vibrations for powering of the sensor nodes. The peak power consumption of a WISAN node (75 mW), is very short in duration and lasts only for amount of time necessary to synchronize to a beacon and transmit the collected data. All other time the node spends in the low power mode, consuming about 0.1mW of power. For example, continuous acquisition of a 12-bit analog input at 50Hz will produce 2250 bytes of data over a period of 30 seconds. Assuming the worst possible power consumption and conservative acquisition time of 1ms, acquisition process will consume  $50\text{Hz} \times 30\text{s} \times (1\text{ms} \times 7.5\text{mW} + 19\text{ms} \times 5\mu\text{W}) = 0.0113925\text{J}$  of energy. Assuming 50% utilization of the wireless link (again, a very conservative estimate) the transmission of these data will last  $2250\text{bytes} / (250\text{kbps} \times 0.5/8) = 14\text{s}$ . Therefore, the transmission will expend approximately  $0.14\text{s} \times (52\text{mW} + 7.5\text{mW}) = 8.3\text{mJ}$  of energy. Assuming that a sensor node spends approximately 100ms in the receive mode waiting for a 802.15.4 beacon, the total energy consumption will increase approximately by  $0.1\text{s} \times (60\text{mW} + 7.5\text{mW}) = 6.75\text{mJ}$ . Thus, the total energy spent by a WISAN node for a 30-second continuous acquisition of an analog signal at 50Hz sampling rate is  $11.4\text{mJ} + 8.3\text{mJ} + 6.75\text{mJ} = 26.45\text{mJ}$ . For comparison, the energy consumption for transmission would be 0.9J (vs. 8.3mJ of WISAN), a number two orders of magnitude higher. These numbers directly translate into the battery life of a sensor node and enable battery-free operation from energy-

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harvesting devices capable of producing as little as 1mW. The low power consumption enables truly autonomous and continuous operation from an energy-harvesting device, like those described. In practical terms, a virtually maintenance-free SHM system could be created by utilization of electro-mechanical or piezo-electrical power generating devices for powering of the WISAN nodes.

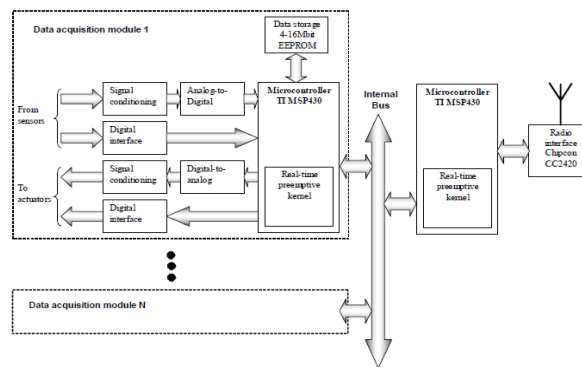


Fig 1:A WISAN node

Selection of the 802.15.4-compatible protocol for the physical and data link layers of the network protocol also resolves the issues with electromagnetic compatibility, reliability and security. The radio frequency (channel) allocation for devices foresees the coexistence in the presence of other popular network protocols, such as 802.11 (WiFi). Functioning in the presence of electromagnetic interference is supported through utilization of channel sniffing. The communications between sensor nodes can be made secure through Advanced Encryption Standard (AES) encryption and authentication. The signal strength meter located in the Chipcon RF interface module allows implementation of localization capabilities in the sensor nodes by performing cross-node measurements of signal strength. Such capabilities can be implemented following the procedure. The node localization can potentially be used in routing algorithms to minimize the number of hops and evenly distribute the power consumption among the sensor nodes. The real-time preemptive kernel schedules the execution of every task in the sensor nodes and supports high-precision global time synchronization and time stamping of the sensor data and actuator commands. For example, in order to reconstruct displacement mode shapes from the modal response of a structure, the precision of the mode shapes reconstruction will depend on the accuracy of time synchronization of the sampling events. The time signals for global time synchronization will be transmitted as a part of the 802.15.4 super frame and incorporated into the beacons. Combined with low latency of the real-time kernel, the precision of global time synchronization is expected to be on the order of microseconds. The services provided by the real-time software of a sensor node implement the embedded intelligence and distribution of computational load. The minimization of bandwidth consumption is achieved through on-the-fly compression of the sensor data. Minimization of the response time is achieved through implementation of fuzzy logic and neural network capabilities that translate into simple ways to perform control tasks without transmitting the data over the network.

Considering the low energy consumption by the network interface of WISAN, we do not think that application of fast, high-power computational devices for performing such operations as Fast Fourier Transform on the sensor nodes is justified energy-wise. For example, estimate that computation of 4000 coefficients for an auto-regressive model on a Motorola MPC555 microcontroller consumes approximately 3J of energy. Transmission of the 16,000 bytes of the raw data for that computation without employing any compression scheme in WISAN would consume about 66.75mJ of energy (a conservative estimate). Therefore, that network transmission is potentially 44 times more cost-effective than on-sensor computations. The data will be transmitted to a dedicated node connected to a power source with lower price of energy, such as a power line or a solar cell. Such a dedicated node would provide a more cost-efficient solution to the computational requirements of the SHM system.

All of the above mentioned considerations also dictate the architecture of the sensor network. We propose to utilize a two-level cluster-tree architecture, providing better fault tolerance than a two-tiered architecture. Fig. 2 illustrates the structure of a two-level cluster-tree network.

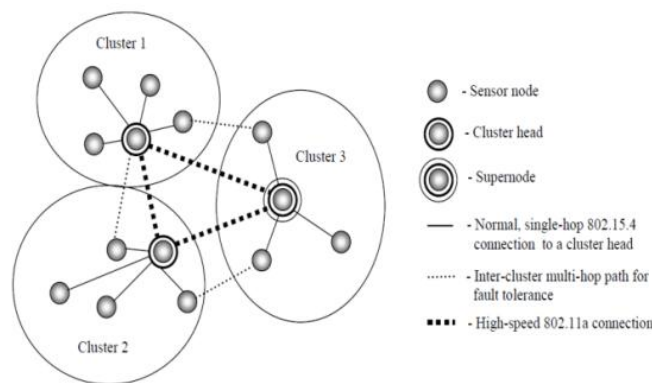


Fig2: Two-level Cluster-tree architecture of WISAN

### VIII. THE MONITORING METHODOLOGY

WISAN allows autonomous instrumentation of civil structures, but to be truly autonomous, such an SHM system should not require significant energy for excitation of the structure, but rather rely on ambient energy, and allow for human-free damage detection process. WISAN will be used to utilize the method of modal strain energy for structural health monitoring of bridges.

The features of the Modal Strain Energy (MSE) make it a perfect candidate for fully autonomous long-term structural health monitoring of bridges. These features include:

*A. Damage detection based on the localized changes in mode shapes.* The MSE is a *local* method where a grid of sensors passively listens to the vibration of the structure. If natural frequencies are known, damage detection for a given location can be performed only using the data from the *three adjacent nodes*. In the method's formula ,

$$U_{ab} = \frac{1}{2} \int_a^b EI(\phi'')^2 dx$$

the integration interval  $[a-b]$  usually (but not always) represents the sampling interval with which the nodes can be positioned on the structure. This interval defines the spatial resolution with which damage can be localized in the structure. If a mode shape has a node at the location of damage, there will be other mode shapes that can detect damage at that location.

*B. Autonomous damage detection from ambient vibrations.* The modal data from a structure can be acquired using WISAN to acquire ambient vibrations caused by traffic, wind and microtremors of the ground. Thus, the monitoring system does not have to excite the structure in any way, lowering the total energy expenditure of the system and allowing for truly autonomous operation.

*C. High sensitivity to damage and availability of the theoretical background for sensitivity evaluation.* Compared to other modal methods, the method of modal strain energy offers higher sensitivity to damage on the beams. It has been used for damage detection on the plates, and has been tested on the actual bridge structures. The best sensitivity to damage can be established through the analysis of the measurement noise.



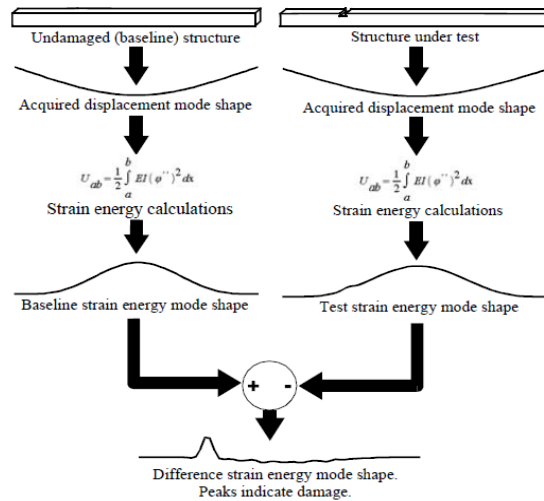


Fig 3: Illustration Of Modern Strain Energy method

*D. Low sensitivity to environmental and operational variations.* Compared to other modal methods, the MSE method is less sensitive to environmental variations. Changes in natural frequencies due to temperature variation may be more pronounced than changes due to damage, while changes in the mode shapes are less pronounced. In addition, such changes can be accounted for by having a different baseline (in a baseline-based method) for each temperature range of interest.

*E. Ability to detect damage on structures without known response.* Damage index method and frequency decomposition MSE method allow detection of damage in structures with unknown damage state. For the MSE method, it can be show that the Fourier series of strain energy mode shapes of an undamaged pinned-pinned beam consists only of two members for any mode, while the Fourier series of a damaged beam contains significantly higher number of harmonics. Damage location in the beam can be established by removing the two harmonics related to the frequency spectrum of an undamaged beam and performing the inverse of the Fourier series. The same technique can be applied to other symmetrical boundary conditions and beams of more complex shape.

*F. Model-free method.* The method of modal strain energy does not require an analytical or numeric model of the structure, thus lowering the cost of the monitoring system. As an example, model updating methods require an accurate (and expensive) numerical model of the structure under test. To locate damage in the structure, an inverse problem (changing the model, so that it matches the actual response of the structure) has to be solved. Such a solution may not be unique. The method of modal strain energy can uniquely locate damage in a structure.

*G. Automated damage detection algorithms.* Automated damage detection algorithms and software were developed during the design of automated damage detection system for Armored Vehicle Launched Bridge. A well-developed theoretical base implemented in practical software solutions paves the way for a fully automated system of structural health monitoring for bridges. A simplified scenario of structural health monitoring using the modal strain energy method and involving a baseline is illustrated in Fig. 2. Structural damage is detected by identifying changes in the strain energy mode shapes caused by the changes in stiffness at the damage location. The modal response of the structure under test is used to reconstruct the displacement mode shapes. The strain energy formula is used to calculate the test strain energy mode shapes. The test strain energy mode shapes are compared to the baseline, representing the original state of the structure. Any damage to the structure will create damage indicators on strain energy difference mode shapes.

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## IX. CONCLUSION

The presented concept of a sensor network for fully autonomous structural health monitoring also provides a solution for the energy crisis. Also the intelligent capabilities of the sensor nodes minimize energy consumption of the sensor network as whole by performing energy-efficient operations such as data compression, while delegating power-intensive computations to the supernode.

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